Amendments to the Drawings

The attached replacement drawing sheet has been revised to include a reference sign pointing to the system 10. This sheet, which includes Figure 1, replaces the original sheet including Figure 1.

Attachment: Replacement Sheet containing Figure 1

REMARKS

Applicants have carefully considered the rejections raised in the Office Action dated April 21, 2005. As a result, the application has been amended in order to comply with the Examiner's requirements, as outlined herebelow.

Firstly, in connection with the requirement under 37CFR 1.98(a)(2), submitted herewith is a legible copy of the non-patent literature, J.-Y. Jeng, et al.: "Metal Rapid...Cladding Technology". The Examiner is respectfully requested to consider this reference which was originally filed in the informational disclosure statement dated May 14, 2005.

The drawing sheet containing Figure 1 has been amended to insert the reference sign for the element 10.

The description and claims have been amended to replace the word "interference" with the word "inference". Applicants submit that this was a typographical error in the application as filed. Applicants submit that this amendment adds no new matter since those skilled in the art clearly understand that "inference engines" is a term of art, and that "interference engine" is clearly in error.

With reference to the rejections set out in paragraph 4 of the Action, claims 1, 3, 7, 8, 15 and 20 have been amended to address the lack of antecedent basis issue pointed out by the Examiner. In regard to the limitation "the melt pool" in claim 8, the Applicant respectfully submits that the antecedent basis can be found in its parent claim 7, line 4. Likewise, the limitation "the reference plane" in claim 18 has its antecedent basis in its parent claim 17, line 3; and the limitation "the width of the clad" in claim 21 has its antecedent basis in its parent claim 20, line 3.

With reference to the rejections set out in paragraphs 5 and 6 of the Action, claims 8 and 31 as well as claim 15 have been amended to delete the term "substantially".

In addition to the above-mentioned amendments, Applicant has also made further amendments to address other claim deficiencies and to correct some typographical errors in an effort to provide clear definition of the terminology and phrases used in the claims.

Claim 1 has been amended to incorporate the subject matter of claim 3 and part of the subject matter of claim 2. In view of the amendment to combine claims 1 and 3, the remaining subject matter of claim 2 is considered redundant. Claims 2 and 3 have been cancelled.

Claim 15 has been amended to incorporate some of the subject matter of claim 16 and the subject matter of claim 19 and claim 19 has been cancelled. Claim 18 has been amended to depend from claim 17. Claim 20 has been amended to address the 112, second paragraph matter pointed out by the Examiner.

Claim 17 has been amended to add the phrase "using a transformation matrix that is obtained based on orientations of the at least two image detectors with respect to the reference plane *and a clad trajectory*." The feature of the clad trajectory is found in the application as filed on page 14, line 16.

New claim 37 combines the subject matter of claims 15 and 26. New claim 38 is similar to claim 16 and the remaining dependent claims 39 to 52 are similar to claims 17 to 31.

In view of the fact claim 26 has been deemed allowable if the 112, second paragraph rejections are overcome, Applicants respectfully submit new claims 37 to 52 are allowable.

Claims 32 and 33 have been cancelled and new dependent claim 53 has been added. Claims 34 to 36 have been amended to depend from new dependent claim 53.

New claim 54 depending from claim 1 is similar to claim 17.

Description pages 5-7 containing the Summary of Invention have been amended to include the paraphrases of the amended independent claims.

It is respectfully submitted that the amendments made herein are to more particularly and succinctly recite the invention. All the amendments are supported by the application as originally filed, and therefore no new matter has been added.

Patentability of Claims Over the Cited References

The Examiner has rejected claims 1, 2, 5, 6, 9-12, 15 and 30 under 35 U.S.C. 102(b) as being anticipated by U.S. Patent. No. 6,122,564 to Koch et al. (Koch). The Examiner is requested to reconsider and withdraw this rejection for the following reasons. The Examiner has rejected claims 1, 5 and 12-15 under 35 U.S.C. 102(b) as being anticipated by U.S. Patent. No. 6,459,951 to Griffith et al. (Griffith) The Examiner is requested to reconsider and withdraw this rejection for the following reasons.

The Examiner has stated that claims 3, 4, 7, 8, 18-29 and 31 are allowable if amended to overcome the rejections under 35 U.S.C. 112, second paragraph

and if rewritten to include all the limitations of the base claims. Responsively, claim 1 has been amended to incorporate the subject matter of claim 3. In view of the amendments to claims 1, 5 to 9 and 12, Applicants respectfully request the Examiner withdraw the 112 second paragraph rejections and submit claims 1, 5 to 14 amended herein are in condition for allowance.

The Examiner has indicated claim 19 is allowable if amended to overcome the 112, second paragraph, rejections of the base claim 15. Therefore, in view of the amendments to claims 15 to 31, Applicants respectfully request the Examiner to withdraw the 112 second paragraph rejections and submit claims 15 to 31 amended herein are in condition for allowance.

Since new claim 37 combines the subject matter of claims 15 and 26, and since claim 26 has been indicated as been allowable, Applicants respectfully submit that for the same reasons claim 15 is allowance, new claims 37 to 52 are also allowable.

The Examiner has rejected claims 1, 2, 5, 6, 9-12, 15 and 30 under 35 U.S.C. 102(b) as being anticipated by U.S. Patent. No. 5,961,861 issued to McCay and claim 33 has been rejected as obvious over the combinations of McCay and Griffith or Koch. Claims 32 and 33 have been cancelled and new claim 53 has been added which depends from claim 15 but recites the powders being a mixture of Fe and Al. In view of the arguments above with respect to the allowability of claim 15, Applicants respectfully submit new claim 53 is allowable as well as claims 34 to 36 depending therefrom.

In view of the foregoing discussion, the Applicants submit that the claimed invention is new and inventive over the prior art of record, and therefore, reconsideration and withdrawal of the rejections set forth in the Office Action is respectfully requested.

An earnest effort has been made to place this application in condition for allowance which action is respectfully solicited.

Should the Examiner have any questions or require anything further, it would be appreciated if the Examiner would contact the undersigned attorney-of-record at the telephone number shown below for further expediting the prosecution of the application.

As this response is being filed after the shortened statutory period, a separate request for a three (3) month extension of time until October 21, 2005, is submitted herewith. Any deficiencies in the extension fees may be charged to Deposit Account 04-1577.

Respectfully submitted,
Dowell & Dowell, P.C.

By:

Ralph A. Dowell

Date: 10-14-05

DOWELL & DOWELL, P.C.
Suite 406
2111 Eisenhower Avenue
Alexandria, Virginia
22314
Telephone - (703) 415-2555
Facsimile - (703) 415-2559
E-mail - dowell@dowellpc.com

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Metal Rapid Prototype Fabrication Using Selective Laser Cladding Technology

J.-Y. Jeng[1], S.-C. Peng[2] and C.-J. Chou[3]

[1]Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan; [2]Su-Wei Technology, Taipei, Taiwan; and [3]Taiwan Plastic Company, I-Nan, Taiwan

Non-metallic rapid prototyping has been successfully applied in several industries, but a metal rapid prototype is required for functional prototypes and tooling applications. A metal rapid prototype fabricated using selective laser cladding is presented in this paper. Laser cladding is one type of laser surface treatment process. During this process, an alloy is fused onto the surface of a substrate. Laser cladding devices, i.e. powder feeder, CNC workstation table, laser shutter, and shielding gas controller, were integrated to make automatically any cladding profile possible. The metal prototype was then fabricated layer by layer. This is called the selective laser cladding system (SLC). The fabrication of the metal rapid prototype using SLC technology is described and the detailed design and construction of the SLC is presented in this paper.

Keywords: Laser material processing; Rapid prototyping

1. Introduction

Rapid prototyping systems have been successfully employed in several industries to fabricate concept models, prototypes, and even tooling, for the purpose of rapid manufacturing [1,2]. Layer manufacturing technology is the key technology of the rapid prototyping (RP) system, and it allows the fabrication of 3D parts layer by layer [3]. The principle underlying RP is that the original 3D geometrical part is decomposed into 2D profile layers. Then, material is increased layer by layer for most RP systems rather than by removing material as in machining processes. Hence, complex geometrical parts can be fabricated automatically and rapidly, since machining processes, and the associated fixture and tooling are not required and because the RP process is automated from CAD to the prototyping system [4]. However, most of the commercially available materials, such as photopolymers, powders, paper, wax, plastic materials, and even rubber, are suitable only for the application of concept models, visual prototypes, and limited functional prototypes. The physical properties of these materials make them unsuitable for functional prototypes or tooling applications. Among these materials, only powder sintering has great potential applicability for functional prototypes or even for direct tooling fabrication. Hence, several workers have concentrated on the development of direct laser sintering of metals [5,6], alumina with polymer binders [7], and metal with polymer binders or with low-melting-point components [8,9]. LENS (Laser-engineered net-shaping) is the only recent commercial direct-metal fabrication system [10] available. Jet technology is another important process for RP systems. By using a nozzle to squeeze low-melting-point alloys or a powder-binder mixture, metallic or ceramic parts can be fabricated for functional prototypes or tooling [11].

The objective of laser cladding is to fuse an alloy onto the surface of a substrate with minimum dilution of the substrate. Areas are usually clad by the overlapping tracks of single clad tracks [12]. Laser cladding was originally developed for surface treatment to modify surface wear or corrosion properties. A new material was clad on the substrate by metallurgical bonding with low dilution [13]. Usually, only one layer is fused on the substrate in the conventional laser cladding processes. In fact, laser cladding can be considered as a type of material incress manufacturing technology, if multiple layers and any designed pattern cladding are possible. Gerken et al. and Peng et al. applied laser cladding technology in the application of RP [14,15]. The LENS system uses a focused Nd:YAG high-power laser to melt an area on a metal substrate while a nozzle simultaneously delivers metal powder to the molten weld pool [10]. This system is similar to the SLC system. The most important application of LENS is for direct injection mould fabrication [16]. A theoretical investigation of the influence of the process parameters on the laser cladding geometrical properties was conducted using thermal modelling and computer simulation [17]. High-power laser diodes have been coupled with fibre optics to fabricate solid freeform parts from metal powder [18].

RapidTool uses metal powder with a polymer binder to fabricate rapid metal tooling using the SLS (selective laser

Correspondence and offprint requests to: Professor Jeng-Ywan Jeng, Department of Mechanical Engineering, National Taiwan University of Science and Technology, 43 Keelung Road, Section 4, Taipei, Taiwan. E-mail: jeng@mail.ntust.edu.tw

sintering) process and other post processes [6]. A laser is applied to the thermoplastic-coated metal powder bed to fabricate the part layer by layer. The photopolymer is then vaporised and the part is infiltrated with copper at a high temperature. The most significant problem of RapidTool is that the shrinkage resulting from post-processing is not reproduceable, and it is nonlinear in both the horizontal and vertical directions. In the SLC process presented in this paper, the metal powder was delivered directly into the laser generated melted pool rather than being sintered on the powder bed. The other major difference between SLS and SLC is that a high powered laser is employed in the SLC process, hence the direct metal prototype is fabricated and no further post-processing is needed. More detailed information on the direct metal RP machine and on several metal parts fabricated using the SLC system is presented in this paper.

2. Design and Construction of the Selective Laser Cladding System

A Rofin Sinar RS820 1500 W CO_2 laser was employed in the SLC system as the power source. An SNC-200CP *X–Y* table and one *Z*-axis elevator were used to move the workpiece. The control of the powder used in laser cladding is one of the most important parameters affecting the quality of the cladding. Laser cladding with multipowders has a high degree of flexibility and efficiency. In this study, three individual hopper powder units were assembled together, as shown in Fig. 1. Figure 1(*a*) shows a schematic representation of the design and construction of the selective laser cladding system (SLC). Figure 1(*b*) shows the assembly of the triple powder feeder and mixing chamber to mix three different powders on line by gravity and inert gas. Each powder feeder is driven by one of the three d.c. motors. Each powder feeder also has its own feeding tube. These three feeding tubes can be connected into a mixing chamber as shown in Fig. 1, or they can deliver powder to the laser generated melted pool directly. Hence, great flexibility over powder control can be achieved in the SLC system.

In industry, laser cladding is usually applied on a local surface area of a component. Automation of the cladding process is necessary for the metal RP machine. As shown in Fig. 1, the NC *X–Y* table, elevator controller, laser shutter, powder feeder controller, A/D and D/A card, and RS 232 card were interconnected and networked to the SLC computer. Using this networked SLC system, the cladding area or pattern, and powder flowrate or composition can be programmed into the computer. This SLC system gives a high level of flexibility and automation, which makes operation of the metal RP machine possible. The use of three different hopper powders in SLC enables the fabrication of RP metal parts with variable chemical compositions.

3. Control Software of the SLC

The three d.c. motors of the powder feeders were driven by a D/A card as shown in Fig. 1. The motor speed was detected by a tachometer attached at the end of the d.c. motor and transferred to the computer through an A/D card. Hence, the powder flowrate was set in the computer according to the calibration information of the powder flowrate. The required chemical composition of the RP metal part was determined by the mixing of the three different powder feeders. The cladding profile was determined by the CNC workstation speed, and the total powder flowrate. Hence, the total flowrate of the powder feeders must be specified, and then the percentage of the first and second feeders can be entered into the computer. Therefore, the individual powder flowrate of the three powder feeders can be calculated. The motor speed and the required D/A card value can then be calculated and transmitted to the D/A card to deliver the required powder into the laser generated melt pool.

The CNC workstation was programmed by an SNC-200CP controller, which communicated with the computer through an RS 232 card. First, the program opened a text file to read the cladding path of the RP metal part and generated the associated NC codes for the *X–Y* table. The associated NC codes included

(a)

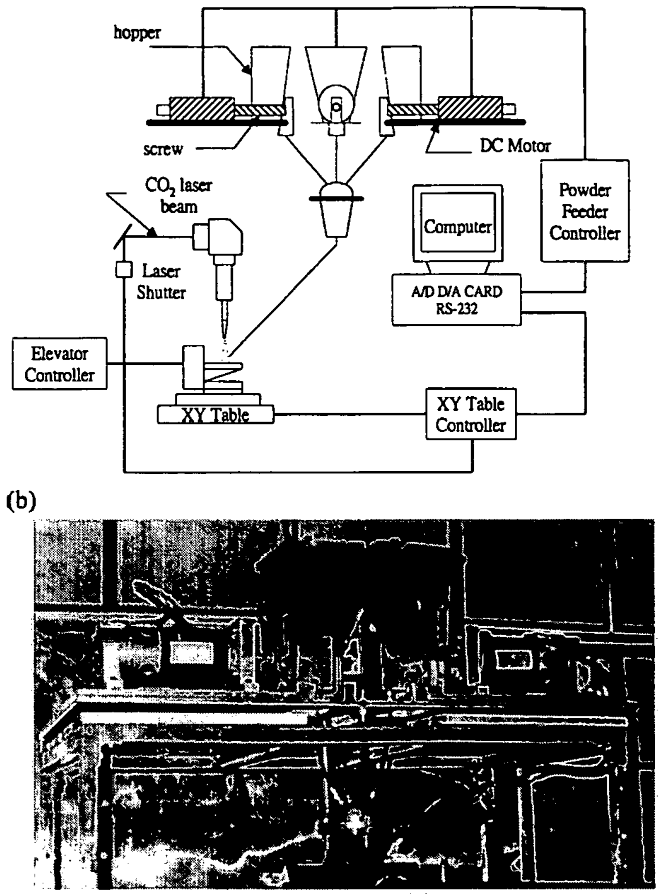


Fig. 1. The design and construction of a selective laser cladding (SLC) system. (*a*) Schematic illustration of SLC. (*b*) Assembly of triple powder feeders and mixing chamber.

the cladding paths, laser shutter control, and shielding gas control, because the SNC-200CP controller not only controlled the *X–Y* table driver but also provided 8 channels for the PLC controller. The laser shutter control, shielding gas, and the associated interlocks were operated with these PLC controllers. The powder delivery was coordinated with the NC codes in the program, because there was a delay time for the powder to arrive to the table.

4. Calibration and Performance of the Hopper Powder Feeders

The powder flowrate is one of the most important parameters of SLC, because it affects the geometrical formation and chemical composition of the metal part. The accurate calibration of each powder flowrate is very important for SLC, because the powder is mixed from three different hopper powder feeders according to the calibration of the individual powder flowrate. In this work, an electrical balance with an RS 232 interface to the SLC computer was employed to calibrate the powder flowrate of each hopper powder feeder automatically. The stability and the accuracy of the hopper powder feeder were also evaluated.

Three different powders, Fe, Cr, and Ni were used in this study to fabricate the metal RP part. The chemical composition of 304 stainless steel was the target to be achieved by the mixing of these three different powders. The performance of the powder feeders was evaluated in terms of stability, repeatability, and accuracy. The stability of the powder feeder is illustrated in Fig. 2. The stability and the linearity of the powder feeder are very good, because the total weight of the accumulated powder increased linearly over time. Figure 3 shows the relationship between the accumulated powder weight for 60 s at different motor speeds. The experiments were repeated three times and recorded. The repeatability of the

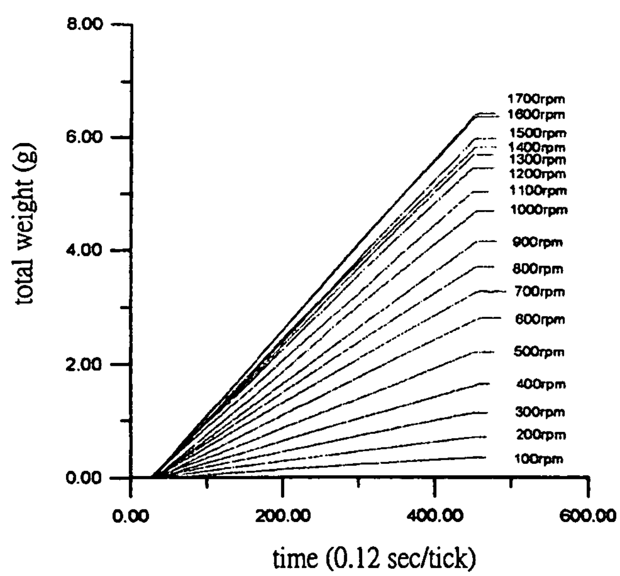


Fig. 2. Stability of the powder flowrate (Cr powder).

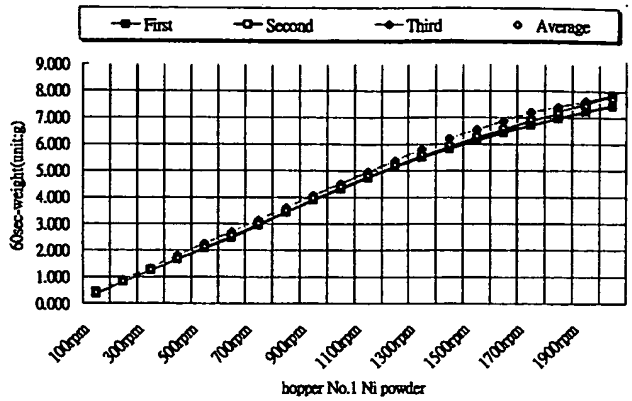


Fig. 3. Repeatability of the powder flowrate (Ni powder).

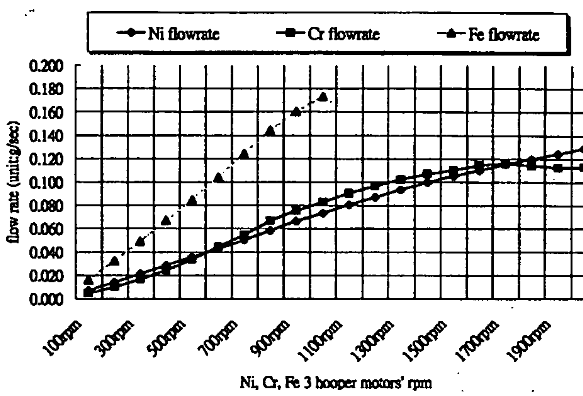


Fig. 4. Flowrate of powder feeders.

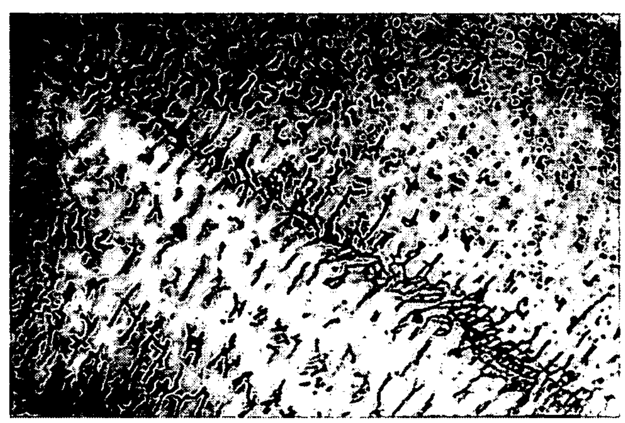


Fig. 5. Metallurgical bonding between tracks.

powder feeder can be observed in Fig. 3 for the Ni powder. The four records are very similar, in particular for motor speeds of less than 1000 r.p.m. The powder flowrates of the Ni, Cr, and Fe powders are shown in Fig. 4. The powder flowrate has an almost linear relationship with motor speed at less than 1000 r.p.m. The Fe powder flowrate is much higher than that for Ni and Cr, because the screw size used for Fe is double that of Ni and Cr. This is necessary because the

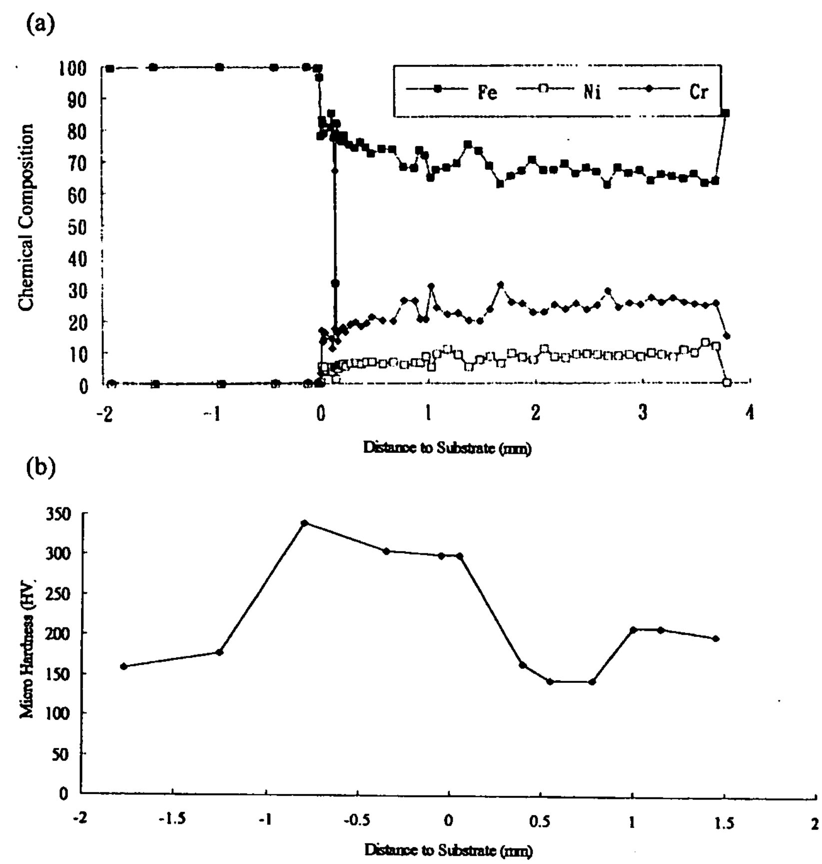


Fig. 6. (*a*) Chemical composition variation of the four-layer cladding. (*b*) Micro-hardness of the four-layer cladding.

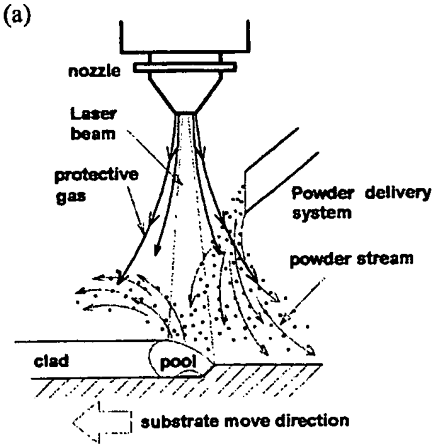
amount of Fe required for the chemical composition of steel is much larger than that of Ni and Cr.

5. Cladding Parameters of SLC

In order to fabricate a metal part using the SLC system, some fundamental cladding parameters were included in the experiments and the cladding properties were also evaluated. First, a single cladding was made to find the optimal cladding parameters of the SLC system. According to the results of the experiments, the best cladding parameters are a laser power of 1400 W, a powder flowrate of 0.3 g/s^{-1}, and a workpiece traverse speed of 3 mm/s^{-1}. Overlapped and multilayered claddings were then made to study the feasibility of the fabrication of the metal prototype. For maximum overlapping, the advance between the adjacent tracks must be 1.5 mm. The microstructure of the cladding between the adjacent tracks is shown in Fig. 5. The bonding of the tracks is very good and this bonding can be categorised as metallurgical bonding. However, if the cladding parameters are not properly selected, the tracks will not bond properly. Some space or porosity exists between the tracks. Porosity develops because the laser power is not enough to melt the lower-layer material to provide metallurgical bonding or because the shape of the lower layer is not smooth enough to provide a suitable wet angle. The chemical composition of the cladding was evaluated using EDAX. Figure 6 shows the chemical composition variation of the four-layer cladding from 2 mm in the parent material to the top of cladding. The average chemical composition of the four-layer cladding was Fe – 71.1%, Ni – 7.1%, and Cr – 21.8%. The target chemical composition of the 304 stainless steel was Fe – 74%, Ni – 8%, and Cr – 18%. The error is about 3.8%. The major reason for this error was that the Cr powder size was about 80 mesh, which is slightly large for this type of screw feeder [13].

The micro hardness of metallic prototype was also tested in the transverse direction of the cladding using a Leitz Rzd-Do micro hardness machine in order to evaluate the mechanical properties of the clad and change of substrate. Figure 6(*b*) shows the micro hardness distribution between the substrate (304 S/S) and cladding (304 S/S mixing powder cladding). The micro hardness at the heat-affected zone was slightly higher than that of the substrate and the cladding. The hardness of the substrate and the cladding was almost the same because of similar chemical hardness. The average hardness of the 304 substrate was about HV233, and the average hardness of the cladding was about HV227. This slight hardness difference resulted from the difference in 304 stainless steel chemical composition between the substrate and the cladding. This means that the hardness of the cladding is similar to that of the substrate.

(a)



(b)

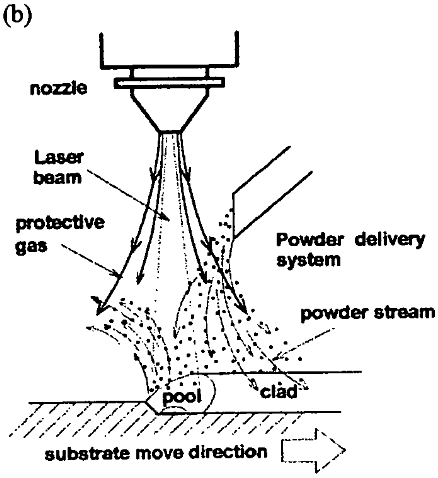
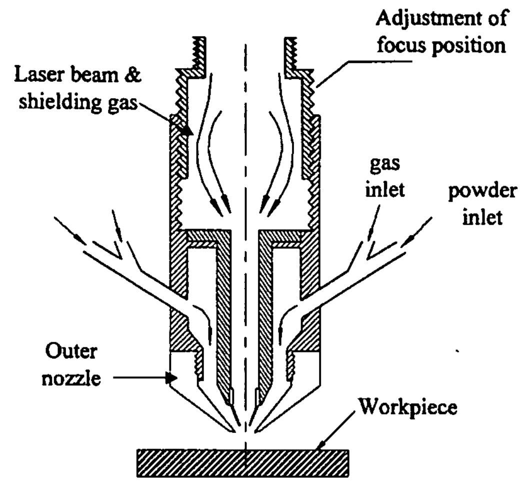


Fig. 7. The effect of the powder delivery on the formation of the cladding. (*a*) Same direction of substrate movement and powder delivery. (*b*) Opposite directions of substrate movement and powder delivery.

(a)



(b)

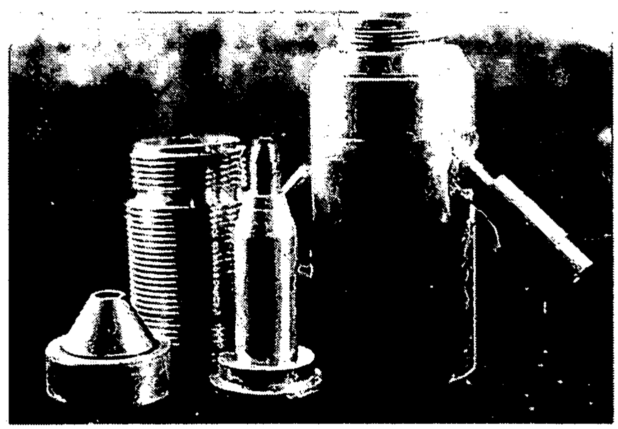


Fig. 8. (*a*) Coaxial nozzle construction. (*b*) Individual components of a coaxial nozzle.

6. Design of Coaxial Nozzle

The effect of powder delivery to the melt pool on the formation of the cladding is shown in Fig. 7. Figure 7(*a*) shows the situation when the direction of powder delivery is the same as the substrate movement, and Fig. 7(*b*) shows the situation when the direction of powder delivery is opposite to the movement of the workpiece. As shown in the figure, the formation of the cladding will be strongly dependent on the direction of the powder delivery and the workpiece movement. It may be possible for the direction of the powder delivery to be perpendicular to the workpiece transverse direction, in which case the formation of the cladding will be very different from that in the parallel direction.

In order to solve the problem of the effect of the powder delivery direction on the formation of the cladding, a coaxial nozzle was designed to feed the powder in the direction of the laser beam. The detailed design of the coaxial nozzle is shown in Fig. 8. Figure 8(*a*) shows the illustration of coaxial nozzle design, and Fig. 8(*b*) shows the individual components of nozzle. The powder was fed from two sides of the nozzle and uniformly distributed between the inside of the outer nozzle and outside of the inner nozzle. In the inside of the inner nozzle, the shielding gas was blown into the workpiece to protect any lens contamination caused by the cladding operation. This design eliminates the effect of the powder delivery direction on the cladding formation.

7. Fabrication of Metal Part

Several 2.5 dimensional parts were fabricated using the SLC system. Two of the fabrication paths are shown in Fig. 9. The first part is a hollow cylindrical part, and the fabricated metallic part with 35 layers is shown in Fig. 10. The other part is a spanner shaped part, and its metallic part with 15 layers is shown in Fig. 11. The density of these metal prototypes is expected to be the same as for a 304 stainless steel part because each layer was fused with metallurgical bonding and

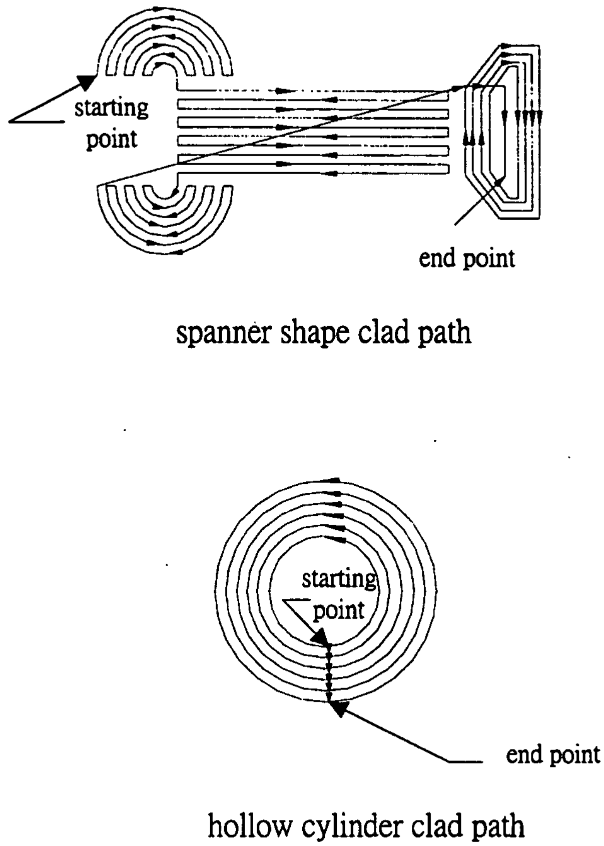


Fig. 9. Cladding paths of two $2\frac{1}{2}$-D metal parts.

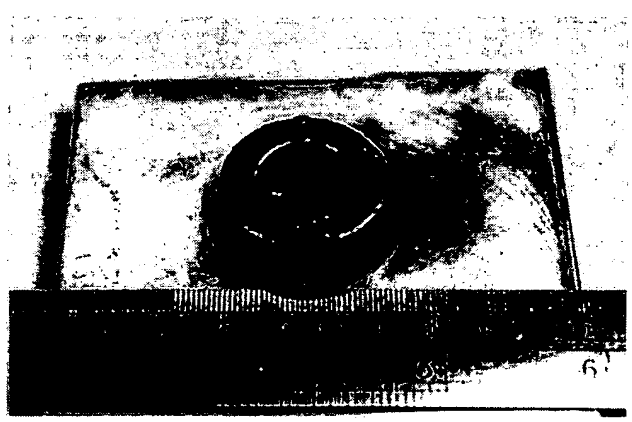


Fig. 10. Hollow cylinder metal prototype fabricated using the SLC system.

is free of porosity. Their strength and hardness are almost the same as stainless steel, because of their similar chemical composition. However, their accuracy and smoothness are far from that required by commercial metal prototypes. The control of powder delivery and laser spot size must be further investigated to improve the accuracy of the metal prototype fabricated using the SLC system.

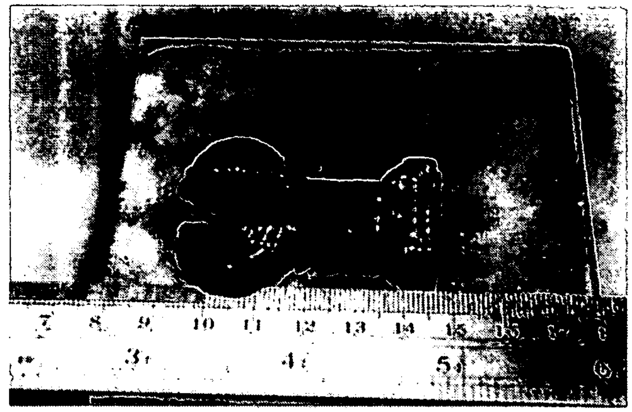


Fig. 11. Spanner shape metal prototype fabricated using the SLC system.

8. Conclusions

Conventional laser cladding is one type of surface treatment process, which can improve surface properties. In fact, it is a type of material incress manufacturing technology. The automation of the cladding process and the design of the coaxial nozzle make metal prototype fabrication possible. The detailed design and construction of a selective laser cladding (SLC) system is presented, and its performance is evaluated. The chemical composition, achieved by mixing from the triple hopper powder feeder, of the fabricated metal prototype is close to that of 304 stainless steel. Metal prototype fabrication using the SLC system is feasible. The accuracy and smoothness of the metal prototype needs to be further investigated. A YAG laser can be employed to improve the accuracy of the laser spot size, and the redesign of the powder feeder can improve the accuracy of the metal prototype. Direct mould fabrication would be possible, if the accuracy of the SLC system could be further improved.

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